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TIME-DEPENDENT POLAR DISTRIBUTION
OF OUTGASSING FROM A SPACECRAFT

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CONTENTS

	<i>Page</i>
ABSTRACT	i
INTRODUCTION	1
TEST OBJECTIVES, SPACECRAFT, AND TEST FACILITY	2
INSTRUMENTATION FOR SELF-CONTAMINATION AND OUTGASSING	5
SELF-CONTAMINATION IN THE SES CHAMBER AND THE MEASUREMENT OF OUTGASSING FLUX	5
QCM DATA ANALYSIS—POLAR OUTGASSING FLUX	10
AVERAGE TOTAL OUTGASSING RATE AND OUTGASSED MASS	13
PRESSURE, DENSITY, AND MOLECULAR FLUX	15
PARAMETERS AS A FUNCTION OF DISTANCE	17
SUMMARY AND CONCLUSIONS	17
REFERENCES	20

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INTRODUCTION

A technique has been developed to measure the outgassing flux from a spacecraft undergoing a thermal-vacuum test. Mass flux data were measured by a single, stationary pair of quartz crystal microbalances (QCM's) as the spacecraft assumed different angular positions at discrete time intervals. These data and their relation to the angular position of the spacecraft while undergoing a thermal-vacuum test, were sufficient to describe the outgassing from the spacecraft.

The technique provided data previously unobtainable during vacuum test which have important applications. They show the self-generated gaseous environment of the spacecraft and how this varies with time, angular location, and distance. This information may be used to estimate: (1) optical path lengths for radiation measurements; (2) degree of contamination that outgassing could produce on a surface in its path at a given temperature; (3) time span available for operation of experiment packages without danger of electrical, optical, and other contamination malfunctions; (4) internal pressure of the spacecraft if its venting properties are known; (5) probable identification of outgassing materials from slopes of their outgassing curves; (6) dynamic effects on the spacecraft from unsymmetrical outgassing; and (7) locations in the spacecraft of objectionable sources of outgassing.

This technique also can be used with a stationary spacecraft, provided that a sufficient number of microbalances are installed around it. Use of a number of QCM's is recommended for complete tridimensional representation of the outgassing, regardless of motion of the spacecraft. The pressure measured, for the thermal model spacecraft of this test, varied with angular location. At a 1-meter equivalent distance from the spacecraft surface in the direction of maximum emission, pressure varied from 5×10^{-6} torr after 10 hours in vacuum to 5×10^{-8} torr after 200 hours. In the direction of minimum emission, pressure was 4×10^{-9} torr after 10 hours and 8×10^{-10} after 200 hours. Equivalent pressures, densities, and molecular fluxes have been calculated for other distances, including integrated total outgassing rates and mass losses versus time.

TEST OBJECTIVES, SPACECRAFT, AND TEST FACILITY

The test results and the analysis reported here were an adjunct to the verification of the thermal design of a spacecraft under solar-vacuum conditions. The test (Reference 1) was to confirm the effect of solar input to the spacecraft panels and that conduction into and through the structure had been properly estimated. Solar heating effects on antennas and other external components were to be investigated. Thermal model components temperature data were obtained throughout the test. The spacecraft was supported by a rotating shaft (the extendible solar array axis) connected to the north-south panels and mounted on a turntable which in turn was mounted on a gimballed fixture. (Figure 1 shows photographs of the spacecraft in various orientations.) The entire assembly without the extendible array was exposed to the environment produced in the space environment simulator (SES) of Goddard Space Flight Center. The simulation consisted of two synchronous orbit simulations lasting three days each, in which the spacecraft was oriented to the sun at different angles (in 45° or 15° steps) and for different periods of time (3 hours or 1 hour). The test program is graphed in Figure 2.

The model is of a 3-axis-stabilized spacecraft to orbit at synchronous altitude, perform an extensive series of communications experiments, and demonstrate the capability in space of a number of devices and techniques to advance communication technology. The spacecraft is shown in Figure 1 without the north-south arrays and the 7.6 meter (25 foot) extendible solar arrays. The photographs shown in Figure 1 were taken from approximately the same height and direction as the QCM's which provided the data for analysis. The satellite with its expended apogee motor weighs about 340 kg (750 lb). Its approximate dimensions are: in the north-south direction, about 1.65 meters (65 inches); in the east-west, about 1.8 meters (71 inches); and from the motor tip to the gimballed antennas, 1.6 meters (63 inches). These dimensions may be used to define an equivalent spherical satellite with a 137.25-cm (54-inch) radius. The back-to-back QCM's were located on the east side of the spacecraft 1 meter away from the estimated equivalent surface, and about 10° above the horizontal plane passing thru the north-south axis of rotation.

The test was carried out in the SES chamber, which has nominal dimensions of 8.3-meter diameter, 12.19-meter height, and 1372-m³ volume. The chamber is provided with eight roots blowers, eight mechanical pumps, and seventeen 0.8-meter-diameter diffusion pumps (40 m³ s⁻¹ each). In addition, there is 18.6 m² of surface in a Santeler-type arrangement which may be cooled by helium at 20 K. The chamber shroud made of aluminum with Cat-A-lac black finish can be controlled with nitrogen from 86 to 348 K. The solar simulation is provided by 127, 3.5-kW mercury-xenon arc lamps illuminating a test plane of 6.1-meter diameter with 1 solar constant. Spin and aspect angles for payloads are provided by a liquid nitrogen (LN₂) cooled gimbal. Instrumentation data handling for 2500 channels of data collected every 100 seconds and real-time plotting capability for 130 channels is available. Alphatron and ion gauges are used to monitor the chamber pressure.

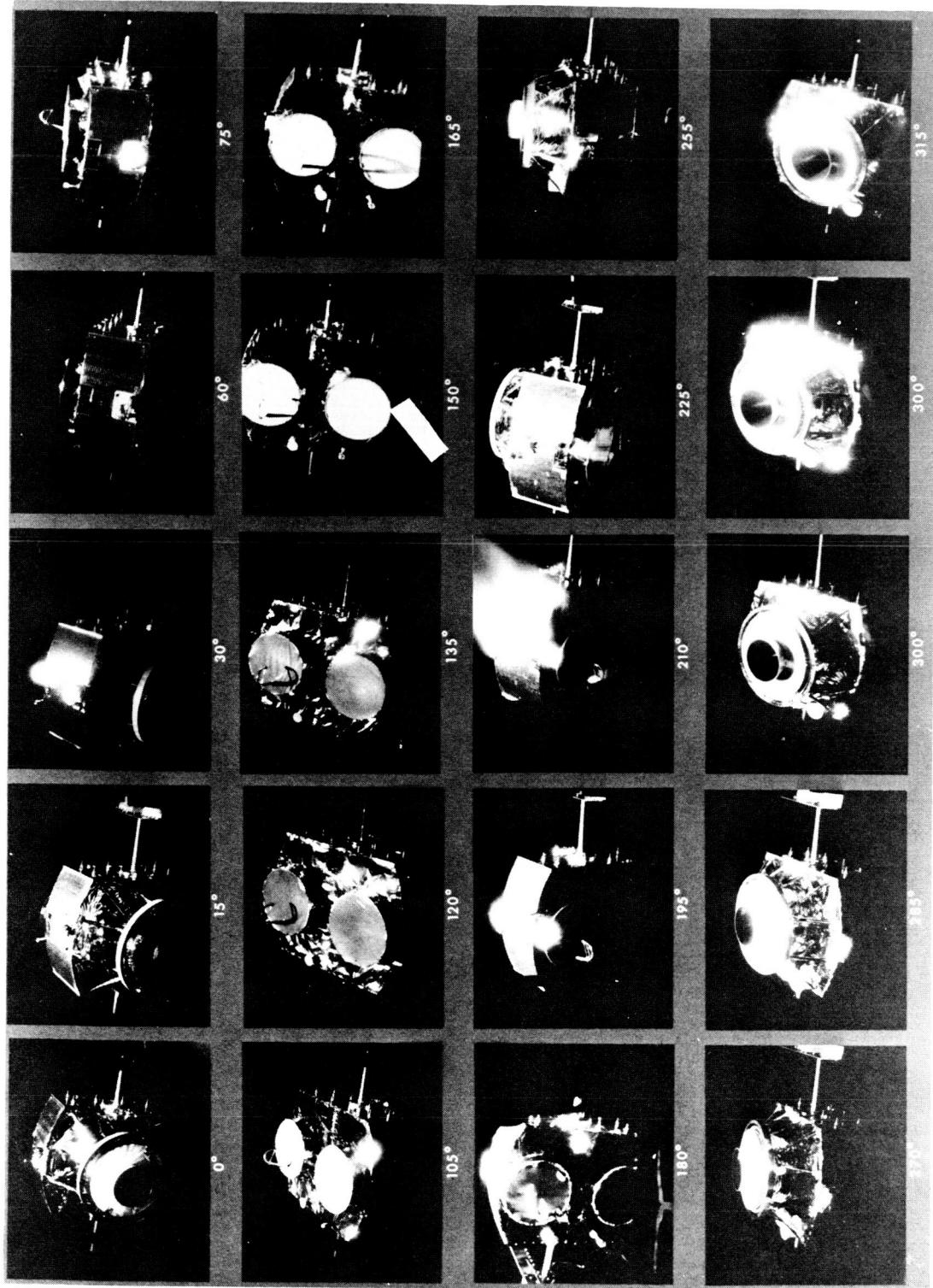


Figure 1. Solar simulation thermal balance test, views of thermal model spacecraft.

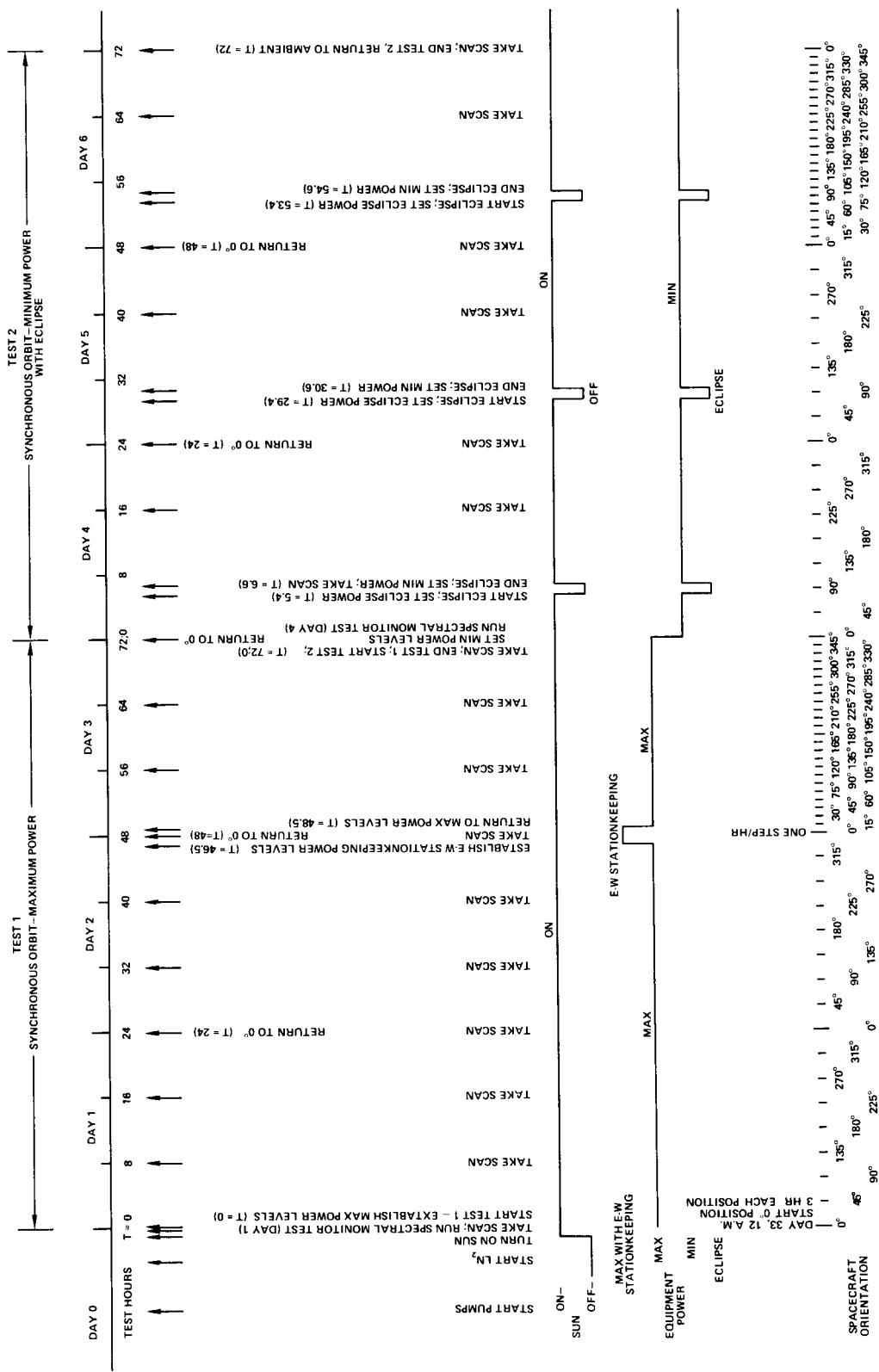


Figure 2. Solar test program.

The pressure maintained in the chamber for the duration of the test is shown in Figure 3. This pressure was measured by the Alphatron gauge suspended in the chamber on the east side of the spacecraft, that is, on the same side as the QCM location.

INSTRUMENTATION FOR SELF-CONTAMINATION AND OUTGASSING

The pair of QCM's mounted back to back, one facing the spacecraft and the other the chamber walls, were located at a distance of 2.37 meters from and perpendicular to the north-south rotating shaft. Their angle above the horizontal was 10° so that when the spacecraft was in its 0° position (the motor facing east), the QCM's were in a position corresponding to the 350° angle of the spacecraft.

Each QCM consisted of two piezoelectric crystals of the same cut and dimensions so as to have the same resonant frequency and temperature response. Of the two crystals, the active one was exposed to the environment while the other was shielded. A mass accretion, Δm , on the exposed crystal produced a beat frequency, Δf , between the two crystals at the same temperature, which is given by Reference 2

$$\Delta m = \frac{A \Delta f}{C_f}$$

For the QCM's used here, the sensitivity factor C_f was $2.22 \times 10^8 \text{ Hz cm}^2 \text{ g}^{-1}$ and the active crystal area A was 0.2 cm^2 . The conversion from frequency to mass per unit area was, therefore, $4.5 \times 10^{-9} \text{ g cm}^{-2} \text{ Hz}^{-1}$. Both QCM's were maintained at LN₂ temperatures. At this temperature, which was the same as that of the chamber shroud, the condensable gases in the chamber which impinged on the crystal condensed upon it. The temperatures of the crystals were monitored by thermocouples attached to them and remained constant throughout the test. On one occasion, when the beat frequency approached $60 \times 10^3 \text{ Hz}$, the QCM's were unloaded by a heating process and then returned to LN₂ temperatures. This is customarily done to prevent nonlinearity in the relation between frequency and mass, which occurs when the beat frequency exceeds about 1 to 2 percent of the crystal's natural frequency.

The frequencies of the QCM facing the spacecraft and of that facing the chamber walls are recorded in Figure 4. The readings were taken manually at intervals of about 15 minutes.

SELF-CONTAMINATION IN THE SES CHAMBER AND THE MEASUREMENT OF OUTGASSING FLUX

In measuring the outgassing of a spacecraft in a chamber with a mass detector pointing to it, one has to be concerned with the amount of wall-reflected molecules. In the chamber, the molecules outgassed may or may not be removed by the chamber walls and pumping systems. Of those not removed a fraction return to the spacecraft and are reemitted if the surface is at a sufficiently high temperature. As shown in Reference 3, the ratio of the

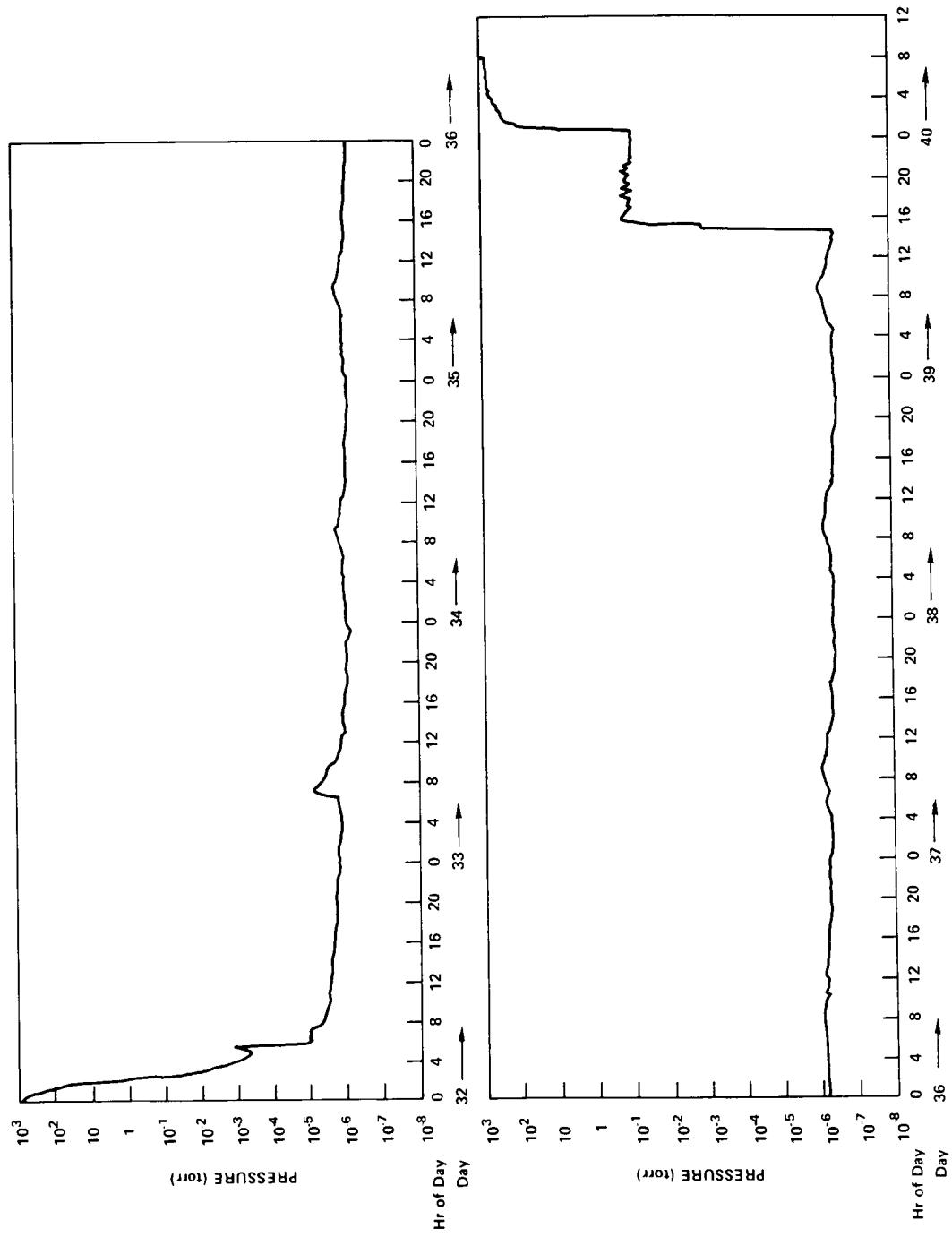


Figure 3. Chamber pressure versus time.

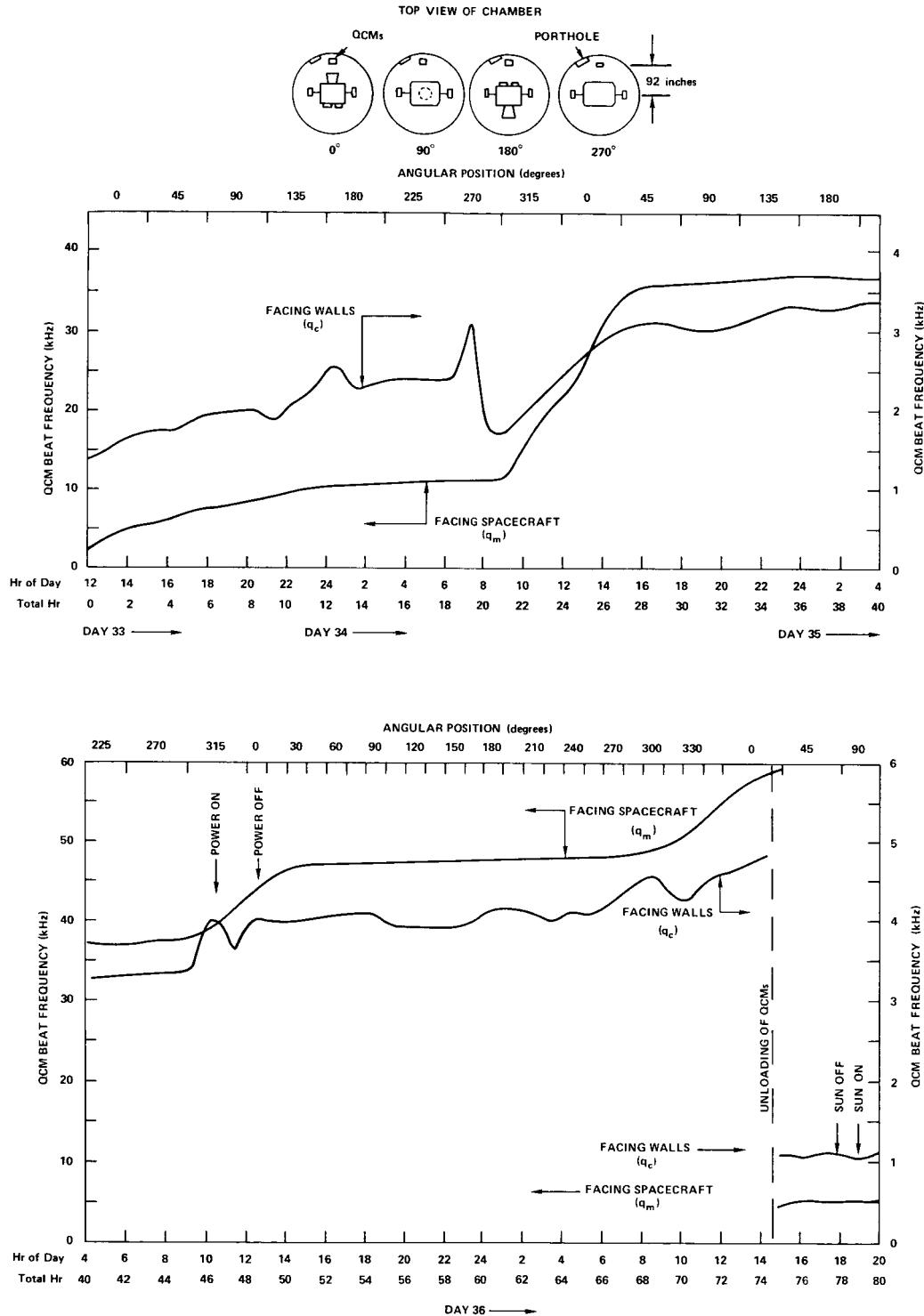


Figure 4. Solar test—QCM beat frequencies versus time and spacecraft angular position.

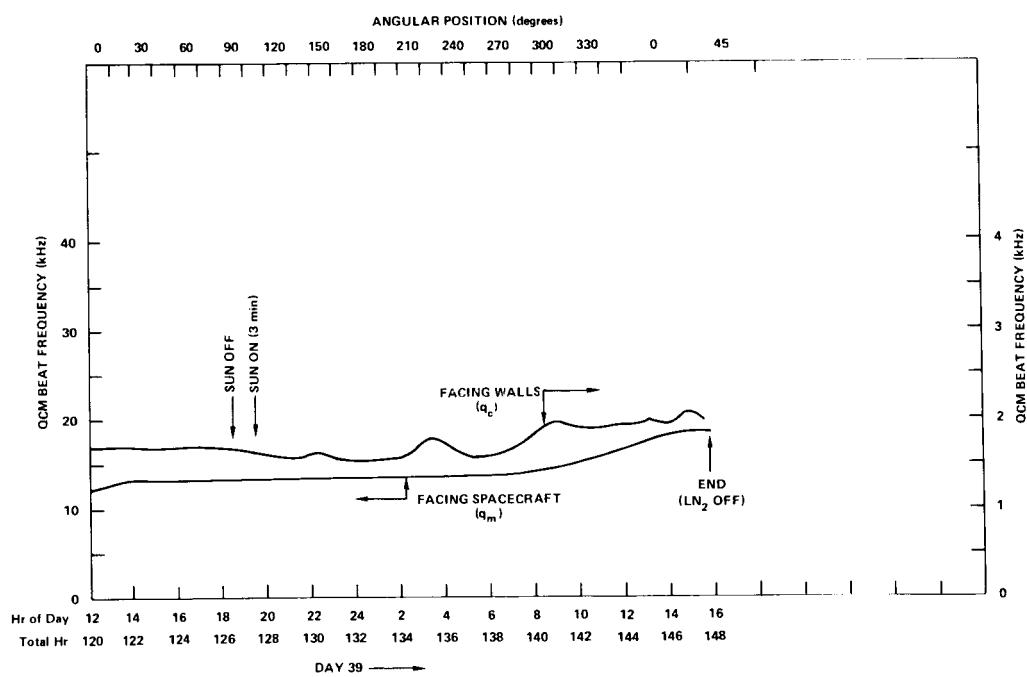
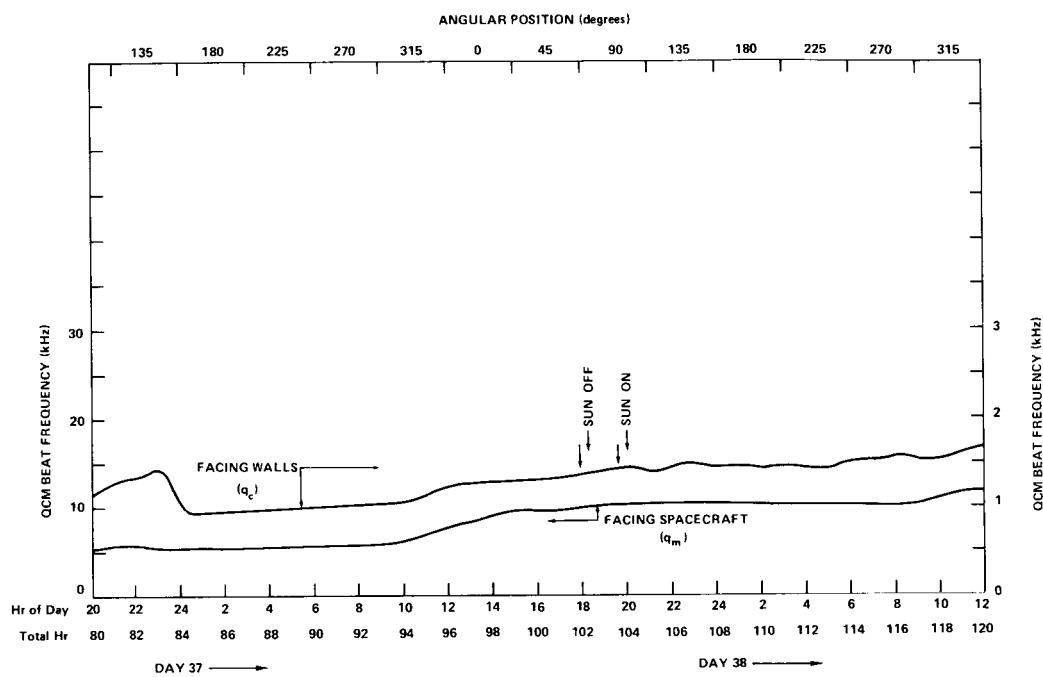


Figure 4 (Continued). Solar test—QCM beat frequencies versus time and spacecraft angular position.

measured mass from the chamber walls q_c to the mass from the spacecraft q_m is given by the relation

$$\frac{q_c}{q_m} = \frac{Z}{B(1+Z)} \quad (1)$$

where Z is a dimensionless parameter including the gas capture coefficient of the chamber (cryogenic walls and pumping system) and B is a geometric factor between the chamber and the spacecraft. Further, it is shown that the actual outgassing mass is

$$q_{mo} = \frac{q_m}{1+Z} \quad (2)$$

This condition is referred to as self-contamination and is the result of the vacuum chamber being unable to simulate completely the molecular sink of space for the spacecraft. A similar self-contamination exists in the condensation region in front of an orbiting spacecraft. The reflection of outgassed molecules in that region occurs as a result of the collisions of outgassed molecules with ambient particles. Hence, it depends on the orbiting altitude and decreases rapidly as the altitude increases.

Figure 4 shows the masses q_c and q_m recorded in terms of frequencies during the solar test of the spacecraft. The abscissa shows day of the year, hours of the day, and consecutive hours since operation of the QCM's. Also, the angular orientation of the spacecraft is shown for each time interval.

From the frequency curves obtained by the two QCM's, one can calculate an average $\Delta f_c / \Delta f_m = \Delta q_c / \Delta q_m \approx 0.065$ for the entire test. The configuration factor B which represents the probability that molecules departing from the chamber walls according to the cosine law strike the spacecraft was estimated as follows (Reference 4). The factor B for two concentric spheres is $B = (r_m / r_c)^2$. For the calculated spacecraft equivalent radius of 137.25 cm and the chamber radius of 415 cm, this value of B would be 0.019. On the other hand, for concentric infinite cylinders, $B = r_m / r_c = 0.33$. An average value of $B = 0.229$ was chosen for the calculation, since neither of the two configurations is correct.

Previous experience, utilizing computer programs to evaluate this factor, has shown that values calculated from these simple expressions are reasonably close to the values calculated by much more laborious methods. Utilizing these values in Equation (1) or the curves in Reference 3, one obtains $Z = 1.43 \times 10^{-2}$. This implies that 1.4 molecules out of 100 condensable molecules emitted by the spacecraft were returning to it after impinging on the chamber surfaces. Also, from Equation (2) and with the value for Z , the actual outgassing of the spacecraft is $q_{mo} = 0.985 q_m$. Thus about 98 percent of the value indicated by the QCM pointing to the spacecraft, is due to outgassing and the other 2 percent is due to reflection.

A comparison of the above value of Z with the returning flux ratio for orbiting satellites indicates that this chamber test simulated an orbiting altitude of about 300 km (Reference 5).

QCM DATA ANALYSIS—POLAR OUTGASSING FLUX

The mass accretion on the QCM facing the spacecraft, recorded in Figure 4, is a function of the spacecraft angular position with respect to the QCM. The position as a function of time is indicated in Figure 2 and repeated for convenience in Figure 4. These figures show that the spacecraft returned to each of the angular positions five times. It remained at these positions for 3 hours in two instances and for 1 hour in the other two. Each position was repeated at 24-hour intervals. It was apparent that from the accretion data, q_m versus time, one could obtain the flux $\phi_m = dq_m/dt$ and the outgassing $\phi_{m_o} = k\phi_m$ applicable to each angular position. The constant $k = 0.985$ provides the correction for self-contamination, as explained above.

Figure 5 shows the change in outgassing flux as a function of time for each position plotted on logarithmic paper. Due to the nature of the data taken, some extrapolation forward and backward in time had to be made for certain positions to obtain the outgassing for each of the positions at the same time. The nature of the plotted curves should make these extrapolations possible without introducing significant errors. Close examination of the curves of Figure 5 provides additional significant information about the nature of the outgassing at each location. In fact, the slopes of the curves reveal the mechanism of outgassing (Reference 6). Outgassing at angular positions 190° and 235° seem to decay according to $t^{-(0.35 \text{ to } 0.45)}$ indicating a process of diffusion. The outgassing between 280° and 340° approaches a decay, following laws such as $t^{-(1.5 \text{ to } 1.8)}$ which are similar to outgassing produced by surface desorption. An identification of the outgassing materials could be made by comparison of the slopes shown by these curves with those obtained experimentally (Reference 7) for several materials. A full knowledge of the list of materials used would be necessary for the identification of the objectionable emissions.

The polar diagram of Figure 6 was plotted from the data shown in Figure 5. It shows the outgassing flux surrounding the spacecraft at 1 meter distance from its equivalent radius, after 10, 20, 60, 100, and 200 hours in vacuum. The flux is in the plane of the figure, the only plane in which the QCM measurements were made. A complete spherical description of the flux would have been made possible by scanning the spacecraft at other longitudes. However, the plot shows the location of the strongest source of outgassing to be between 330° and 345° and the weakest at about 195° . A dimensional description of the spacecraft and the data can locate exactly the source of this outgassing. It is apparent that the motor was outgassing more than any other surface and that the region of the antennas was a weak source.

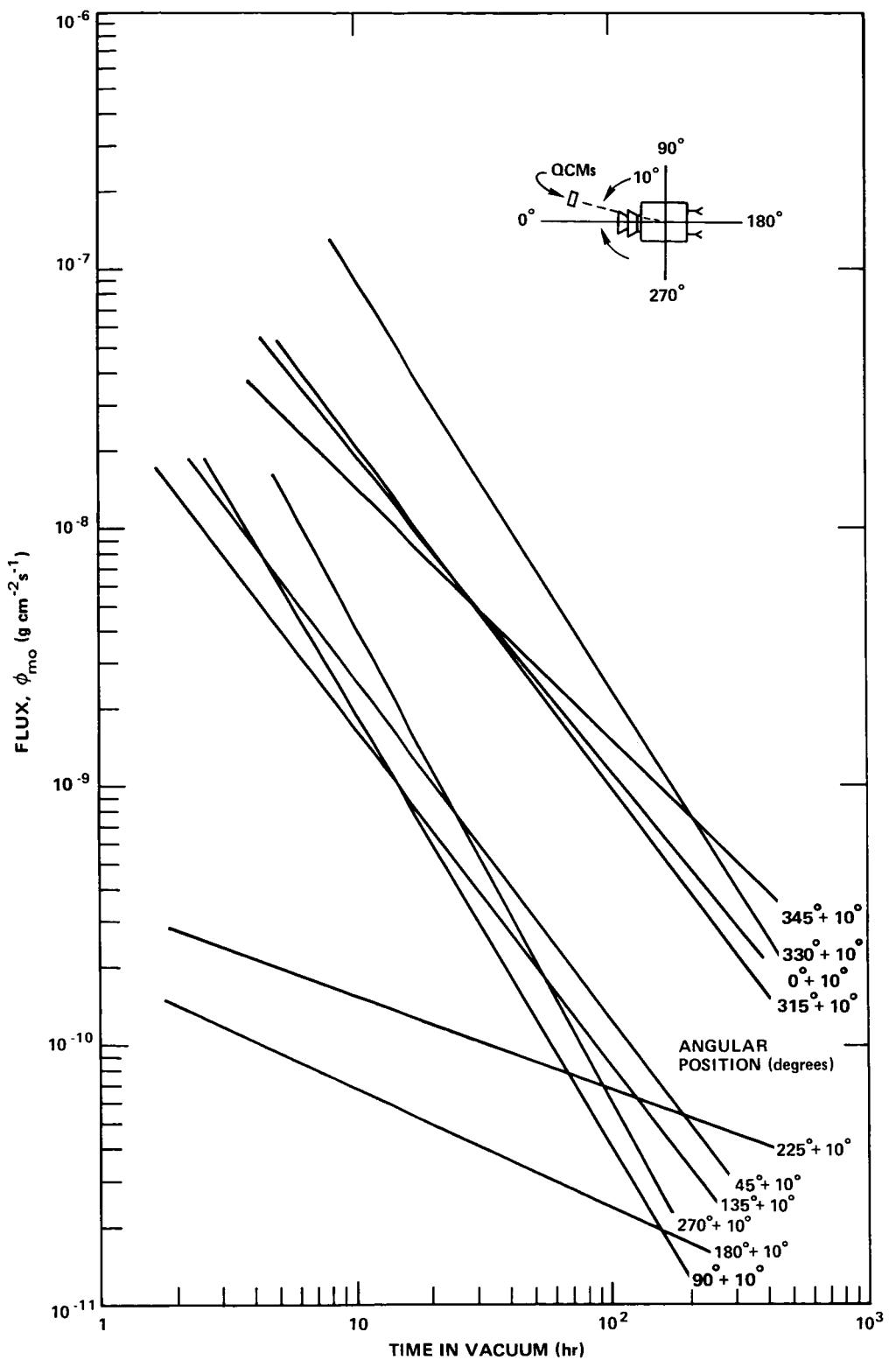


Figure 5. Mass flux at 1 meter from spacecraft surface.

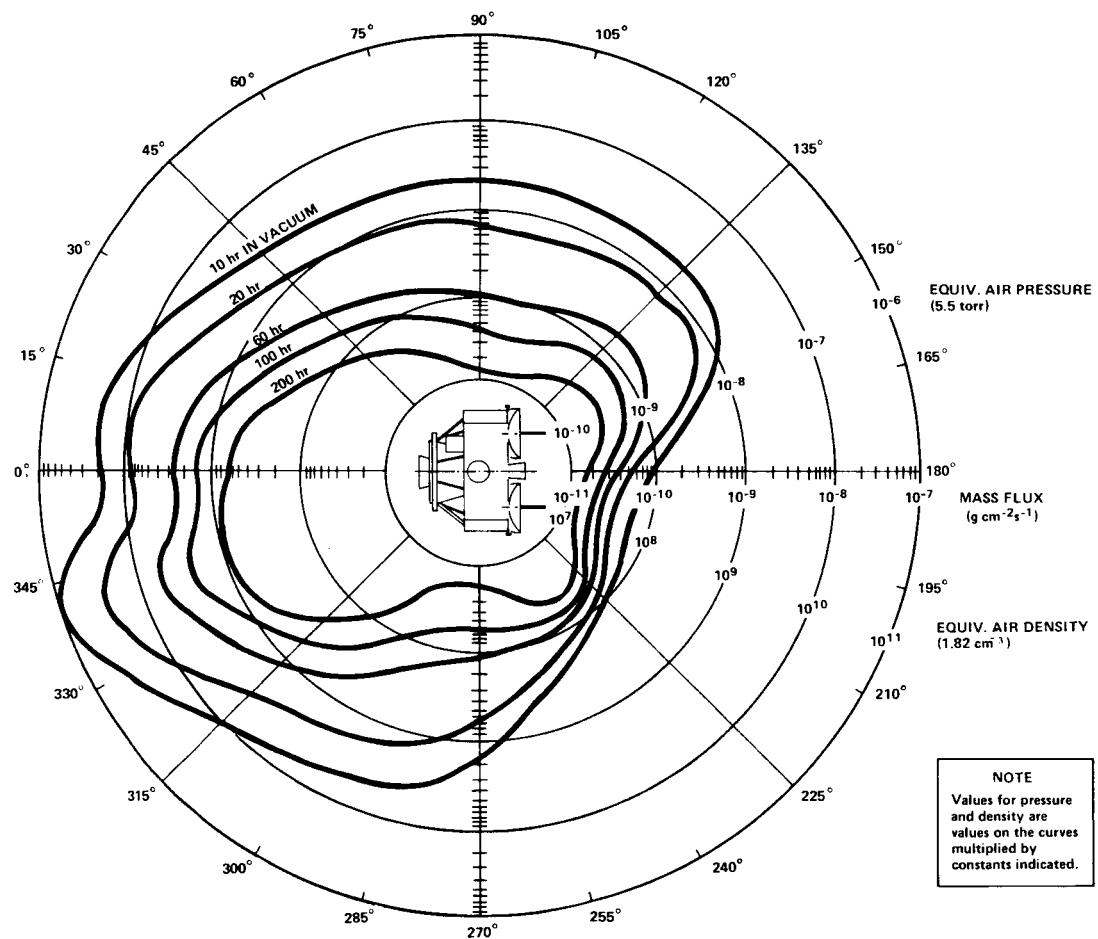


Figure 6. Polar flux, pressure, and density versus time at 1 meter from spacecraft surface in plane of figure.

It is also apparent that in orbit the spacecraft would be subject to an unbalanced force in a direction not parallel to the orbit plane. In addition to the localization of the strongest and weakest sources of outgassing, thrust vector, and nature of outgassing, the polar diagram has other important applications. The total outgassing of the spacecraft can be estimated as a function of time as shown later in this paper. The diagram indicates the degree of contamination (molecular flux) to which a sensitive instrument located in the vicinity of the spacecraft would be exposed as a function of time. This information, with identification of the nature of the outgassing material and the temperature of the critical surface, would be sufficient for the determination of potential contamination. The curves may indicate the spacecraft self-induced environment to which an instrument used to measure the external environment would be exposed and the duration of exposure. Quantitative knowledge of the flux into the condensation region of the spacecraft can also allow a calculation of the collision frequency and hence the ratio of flux return in this region for an orbiting spacecraft. The polar diagram shows that the rate of outgassing of the strongest source decayed two orders of magnitude, from 9×10^{-8} to $9 \times 10^{-10} \text{ g cm}^{-2} \text{ s}^{-1}$ in about 200 hours. It decayed less than an order of magnitude at the location of minimum outgassing.

Some of the benefits which can be derived from these measurements have now been indicated. The following sections discuss the estimation of molecular density, equivalent pressure, total outgassing rate and quantity from these measurements.

AVERAGE TOTAL OUTGASSING RATE AND OUTGASSED MASS

In the absence of additional measurements of the outgassing rates on other longitudes, an estimate of the total outgassing rate can be obtained by assuming flux symmetry around the spacecraft. An average angular flux at time t was obtained using

$$\left| \phi_{av} \right|_t = \left| \frac{\sum \phi_\alpha}{n} \right|_t$$

The flux for a time t was obtained by averaging the fluxes at every 15° of angular position. The results are shown in Figure 7, which shows the average mass flux rate as a function of time. The rate decayed about three orders of magnitude (10^{-7} to $10^{-10} \text{ g cm}^{-2} \text{ s}^{-1}$) in 200 hours and one order in 6 to 7 hours. The equation $\phi_{av} = 1.219 \times 10^{-7} t^{-1.26} (\text{g cm}^{-2} \text{ s}^{-1})$ fitted the data. The average outgassing mass rate for the spacecraft obtained by multiplying the above rate per unit area by the surface area of the sphere that has a radius $r = 137.25 \text{ cm}$ ($A = 7.07 \times 10^5 \text{ cm}^2$) is given by

$$W = 4\pi r^2 \phi_{av} = 8.61 \times 10^{-2} t^{-1.26} (\text{g s}^{-1})$$

After 1 hour, the rate of outgassing was $8.61 \times 10^{-2} \text{ g s}^{-1}$; after 100 hours, $2.6 \times 10^{-4} \text{ g s}^{-1}$. The outgassed mass as a function of time can be obtained by integrating the expression for W

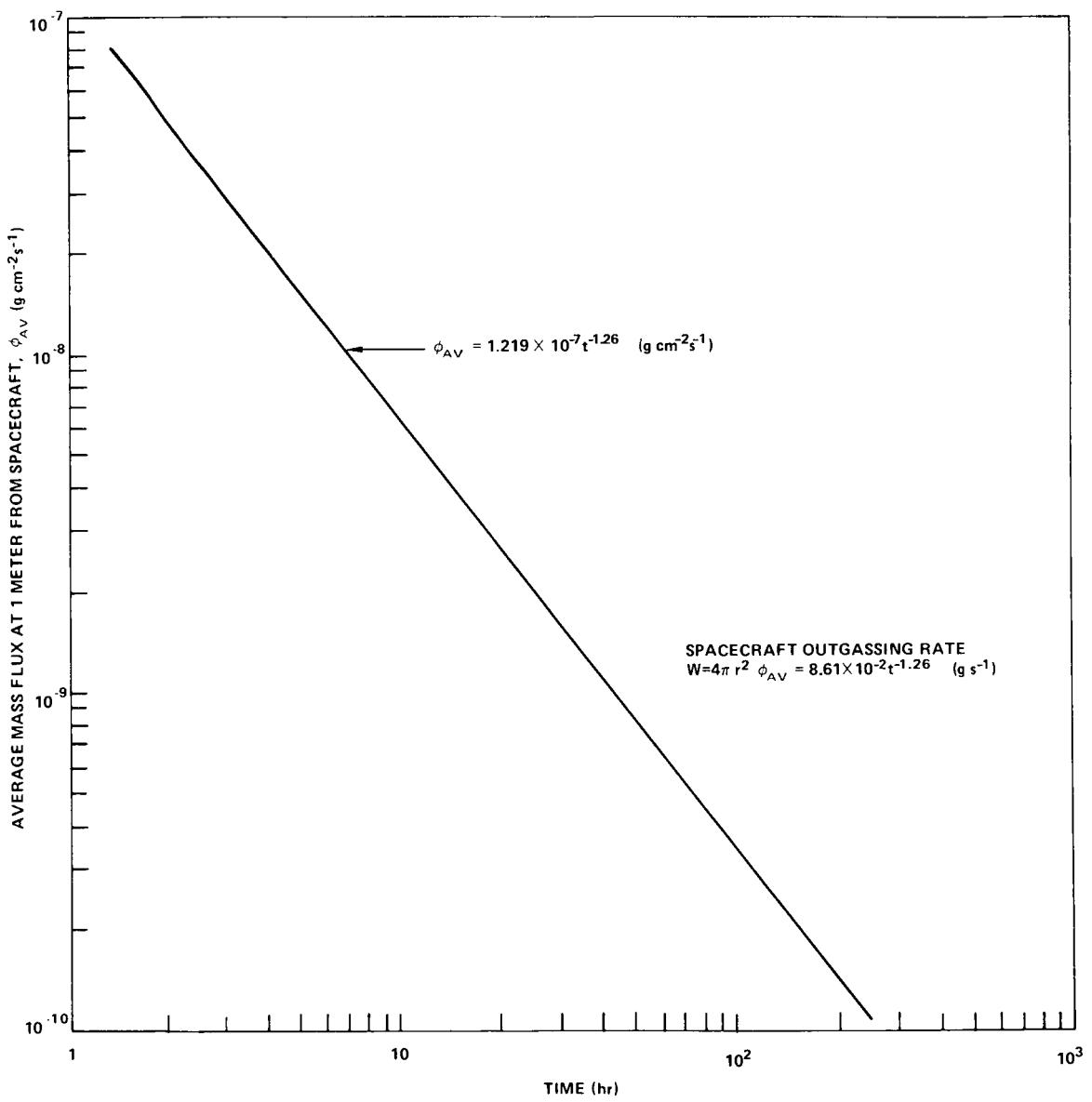


Figure 7. Average mass flux versus time at 1 meter from spacecraft surface.

between time $t = 1$ hour and t to give

$$W_T = 1.192 \times 10^3 (1 - t^{-2.6}) \quad (\text{g})$$

which indicates that from 1 to 10 hours, the spacecraft outgassed a total of 537 grams; after 100 hours, 833 grams; and after 200 hours, 894 grams. Figure 8 shows the outgassed mass as a function of time.

PRESSURE, DENSITY, AND MOLECULAR FLUX

The quantities given so far have been in terms of mass per unit area and unit time (as measured by the QCM's). It is sometimes helpful to express those parameters in other forms such as molecular flux N ($\text{cm}^{-2} \text{ s}^{-1}$), equivalent pressure P (torr), or density n (cm^{-3}). These desirable descriptive parameters require a knowledge of the molecular mass and temperature of the gas. Furthermore, they require the assumptions that the gas molecules have random velocities and directions producing a statistically uniform gas density. These isotropic conditions do not exist in the chamber or in space, since molecules leaving the spacecraft directionally are removed by pumps, cryogenic surfaces, or the sink of space and there is a small probability of intercollisions. However, equivalent pressures and densities as registered by an impact instrument (for example, a QCM) can be defined with the appropriate understanding that they are not densities or pressures with the usual thermodynamic meaning but have a directional significance.

The following relationships are obtained from kinetic theory by employing the perfect gas law $P = nkT$, the mass flux relation $\phi = 1/4 nmc$, and Avogadro's number, A . In these expressions, P (torr) is pressure, k the Boltzmann constant, T (K) absolute temperature, n (cm^{-3}) molecular density, m (g) mass of the molecule, and c (cm s^{-1}) is average molecular velocity (Reference 8). For a temperature $T = 293$ K and molar mass $M = 28 \text{ g mol}^{-1}$ (as for nitrogen) one gets the following relationships in terms of ϕ ($\text{g cm}^{-2} \text{ s}^{-1}$). Equivalent pressure is

$$P = 17.14 \sqrt{\frac{T}{M}} \phi = 55.4 \phi \quad (\text{torr})$$

Molecular flux is

$$N = \frac{A}{M} \phi = 2.151 \times 10^{22} \phi \quad (\text{cm}^{-2} \text{ s}^{-1})$$

Equivalent density is

$$n = \frac{P}{kT} = 1.819 \times 10^{18} \phi \quad (\text{cm}^{-3})$$

For convenience, the scales of the angular plot of the flux, Figure 6, also show the pressures, densities, and molecular fluxes.

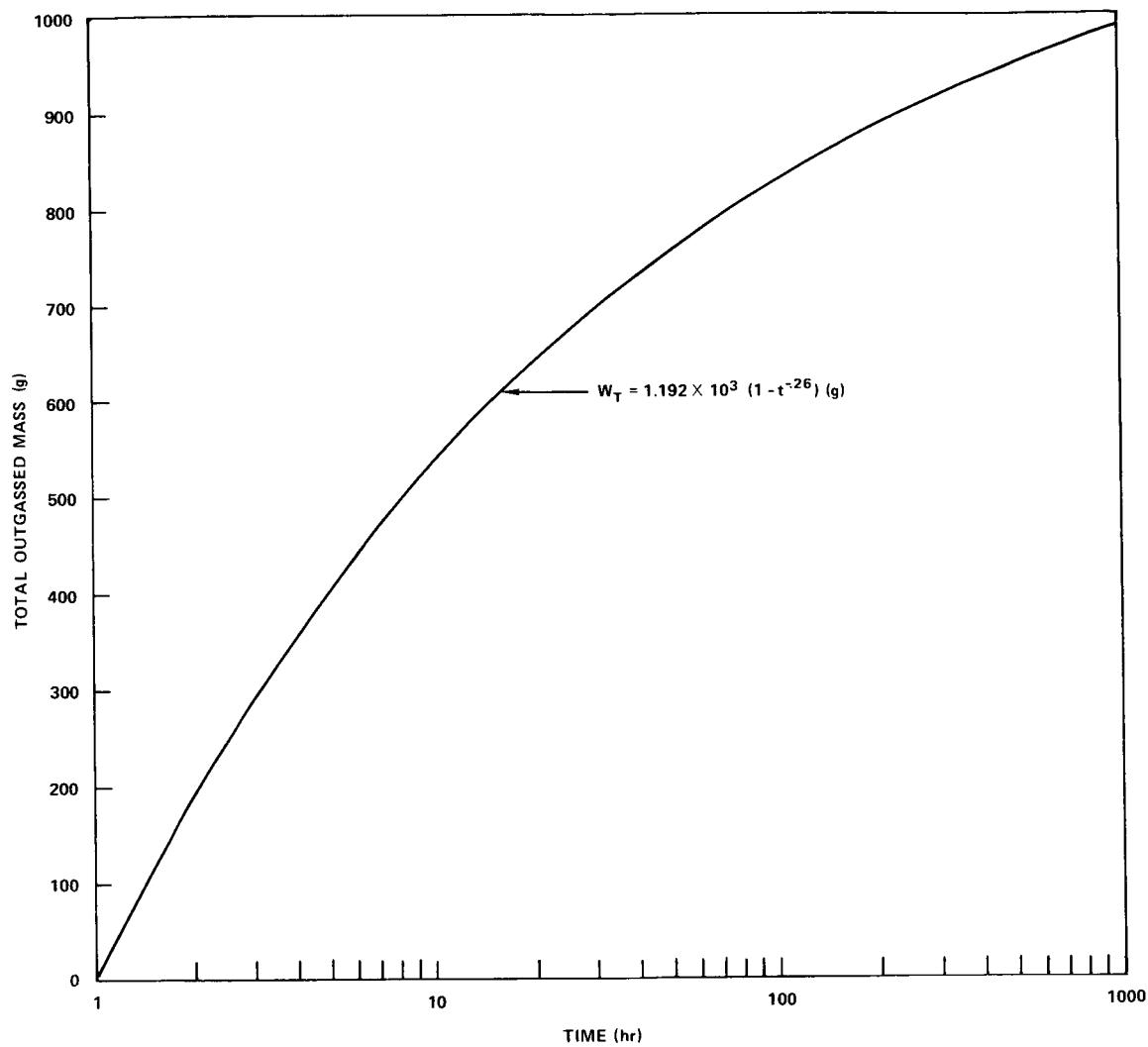


Figure 8. Total outgassing loss versus time.

PARAMETERS AS A FUNCTION OF DISTANCE

The fluxes, pressures, and densities have been shown at a distance of 1 meter from the equivalent surface of the spacecraft. An estimate of these at other distances can be made using the inverse square law. Under steady flow conditions, the flux will be inversely proportional to the spherical surface areas so that

$$\frac{\phi_1}{\phi_2} = \frac{R_2^2}{R_1^2}$$

The pressures and densities as defined above follow the same law. Figure 9 shows the variation of these parameters as a function of the distance from the spacecraft surface. At the surface, the flux, density, and pressure will be about three times as large as those shown in the angular plot of Figure 6.

SUMMARY AND CONCLUSIONS

Two QCM's mounted back to back and located 1 meter away from the equivalent surface of the model spacecraft have provided several important parameters about the self-induced environment in a vacuum. Information obtained by this technique of using and analyzing QCM data is valuable in establishing the self-contamination of a spacecraft in a vacuum chamber and other factors such as: unbalanced thrusting forces resulting from outgassing; the molecular fluxes, pressures, and densities to which sensitive experiments on or near the spacecraft are exposed as a function of time; the location, magnitude and nature of an objectionable outgassing source; the total outgassing rate and mass losses of the spacecraft; data on which to base venting requirements; and the rate of outgassed flux return in the condensation region of an orbiting spacecraft.

Major results obtained from the present test are as follows:

- The self-contamination of the spacecraft (defined as the return of outgassed molecules) amounted to 1.43 molecules returning out of 100 emitted for the conditions existing during the test in the SES chamber. The flux indicated by a QCM pointing toward the spacecraft is about 2 percent larger than the actual flux emitted. The self-contamination experienced during the test is equivalent to orbital self-contamination at about 300-km altitude.
- The polar distribution of outgassing from the spacecraft during about 200 hours indicated that a major source existed at the angular positions of 330° to 340° near the rocket motor. The weakest source was at 195° at the antennas' location.
- The strongest source had a magnitude of $9 \times 10^{-8} \text{ g cm}^{-2} \text{ s}^{-1}$ at 1 meter from the spacecraft, after 10 hours in vacuum. It decayed to $9 \times 10^{-10} \text{ g cm}^{-2} \text{ s}^{-1}$ after 200 hours. These correspond to equivalent pressures of $4.95 \times 10^{-6} \text{ torr}$ and $4.95 \times 10^{-8} \text{ torr}$ and to densities of about 1.63×10^{11} and $1.63 \times 10^9 \text{ cm}^{-3}$.

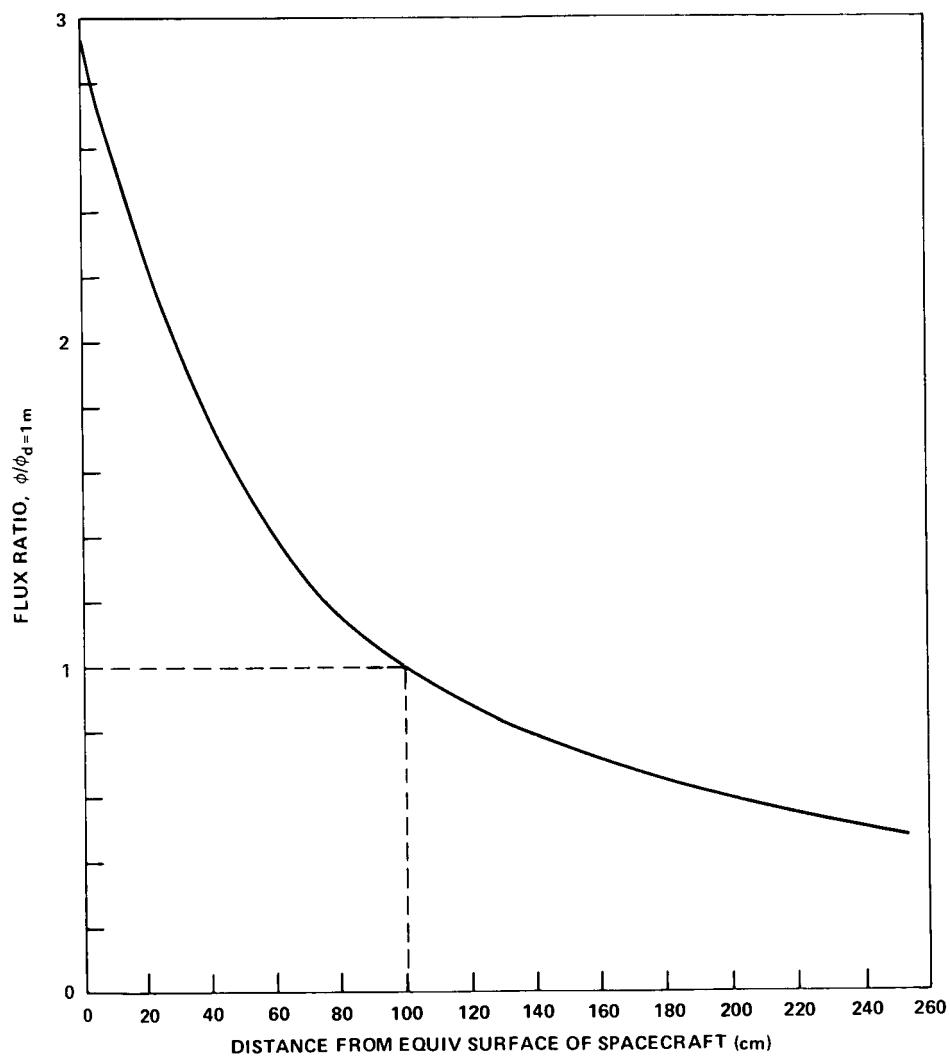


Figure 9. Variation of parameters with distance from spacecraft surface.

- At the spacecraft surface, the values of these parameters are three times as large.
- The total average outgassing flux at 1 meter distance decayed from 1.22×10^{-7} to $1.4 \times 10^{-10} \text{ g cm}^{-2} \text{ s}^{-1}$ between 1 hour and 200 hours in vacuum. An order of magnitude drop occurred in about 6 hours.
- The total outgassing rate was $8.61 \times 10^{-2} \text{ g s}^{-1}$ after the first hour and $2 \times 10^{-4} \text{ g s}^{-1}$ after 100 hours.
- The weight loss due to outgassing was 537 grams after 10 hours and 833 grams after 200 hours.
- The slopes of the outgassing curves for the strong source appeared to indicate outgassing due to a material diffusion process. The process at the weak source appears to be of a surface desorption nature.

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16. Abstract A technique has been developed to obtain a characterization of the self-generated environment of a spacecraft and its variation with time, angular position, and distance. The density, pressure, outgassing flux, total weight loss, and other important parameters were obtained from data provided by two mass measuring crystal micro-balances, mounted back to back, at a distance of 1m from the spacecraft equivalent surface. A major outgassing source existed at an angular position of 300° to 340°, near the rocket motor, while the weakest source was at the antennas. The strongest source appeared to be caused by a material diffusion process which produced a directional density at 1-m distance of about 1.6×10^{11} molecules cm^{-3} after 1 hr in vacuum and decayed to 1.6×10^9 molecules cm^{-3} after 200 hr. The total average outgassing flux at the same distance and during the same time span changed from 1.2×10^{-7} to 1.4×10^{-10} g $\text{cm}^{-2} \text{ s}^{-1}$. These values are three times as large at the spacecraft surface. Total weight loss was 537 g after 10 hr and about 833 g after 200 hr. Self-contamination of the spacecraft was equivalent to that in orbit at about 300-km altitude.			
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